METHOD AND DEVICE FOR ASCERTAINING THE CHARGE ABLE TO BE DRAWN FROM AN ENERGY STORE

Field of the Invention

The present invention relates to a device for ascertaining the charge able to be drawn from an energy store, in particular a battery, up to a specified cutoff, as well as a corresponding method.

Background Information

In the case of electrical energy stores such as batteries, for example, the current charge able to be drawn is an important variable, since it expresses the energy reserve still available before a minimum capacity required of the energy store is undershot. Especially in the field of automotive technology, a precise prediction of the charge able to be drawn is more decisive than the knowledge of the current charge state of the battery defined via the average acid concentration in the lead accumulator, since the latter only provides information about the charge already drawn in relation to the full charge, but not, however, about the amount of charge that is still able to be drawn.

The entire charge still able to be drawn immediately determines the availability of the electrical loads connected to the energy store. The knowledge of the charge able to be drawn may additionally be used for measures of open-loop or closed-loop control technology such as are used, for example, for an energy management system in a vehicle. This makes it possible, for example, to initiate, in time before reaching a

minimum charge reserve, consumption-reducing measures such as switching off or dimming less important loads.

A method is described in published European patent document EP-0376967 to determine the charge able to be drawn from an energy store. In this instance, the charge able to be drawn is estimated via empirically ascertained characteristics maps, which are stored in a processing unit, as a function of a constant discharging current, of the battery temperature and of aging effects on the basis of the Peukert formula. To be sure, this makes it possible to ascertain the charge able to be drawn up to a cutoff, which is characterized by the complete discharge of the energy store; however, it is not possible to determine the charge able to be drawn before undershooting a specified minimum terminal voltage or before undershooting a minimum capacity of the energy store. Moreover, determining the charge able to be drawn on the basis of the Peukert formula is relatively imprecise, since different effects influencing the state of the cutoff such as, e.g., an active mass loss at the electrodes due to the ageing of the battery or the formation of ice at the electrodes at low temperatures are not taken into account.

It is therefore an objective of the present invention to provide a device and a method for ascertaining the charge able to be drawn from an energy store, which allow for a very precise determination of the charge able to be drawn before meeting a specified cutoff criterion.

<u>Summary</u>

The present invention provides a charge predictor, i.e., a device for calculating the charge able to be drawn, which calculates the charge able to be drawn from the energy store with the help of a mathematical energy store model by taking a specified discharge current characteristic and temperature

characteristic into account. The energy store model in this instance is a mathematical model, which uses different mathematical models to represent the electrical properties of the energy store that are based on different physical effects. The mathematical models describe functional relationships between variables of state such as, for example, voltages, currents, temperature, etc., and include different parameters.

The charge computation carried out by the charge predictor takes place starting from the current state of the energy store. Therefore, the mathematical models stored in the charge predictor are first initialized to the current operating state of the energy store. For this purpose, a state variable and parameter estimator is provided, which ascertains the state variables and if applicable also parameters of the energy store model from the current performance quantities such as, for example, the voltage, the current and the temperature of the energy store. For those state variables of the energy store that cannot be measured directly during operation, it is possible to use, for example, a known Kalman filter as a state variable and parameter estimator. Starting from this initialization state, the charge predictor then calculates the charge able to be drawn up to a specified cutoff, i.e. before meeting one or several specified cutoff criteria, which will be explained in detail below.

The energy store model includes in the case of a battery at least one model for the internal resistance R_i of the battery, an acid diffusion resistance R_k and a charge transfer polarization U_D.

The state and parameter estimator ascertains as state variables Z at least an open-circuit voltage U_{C0} of the battery and a concentration polarization U_k. To the extent that the battery capacity and thus also the acid capacity C_0 of the

battery used is unknown, this is to be calculated as well. For this purpose, the state variable and parameter estimator ascertains at least the parameters R_{i025}, $U_{e,grenz}$, R_{k025}, U_{D025} and C_0. These parameters will be explained in detail below.

The cutoff criterion, up to which the charge able to be drawn is calculated, may be, for example, the reaching or undershooting of a specified minimum electrolyte voltage U_{ekrit}, a minimum terminal voltage $U_{Battmin}$ or the reaching of a specified minimum capacity $U_{Lastmin}$. According to an example embodiment of the present invention, the charge able to be drawn is calculated until at least two, or all three, of the mentioned cutoff criteria are reached or undershot.

The cutoff criterion of the minimum electrolyte voltage U_{ekrit} is fulfilled if the electrolyte voltage U_e falls below the specified minimum electrolyte voltage U_{ekrit}. For this purpose, the specified electrolyte voltage U_{ekrit} preferably takes into account the active mass loss due to battery ageing and/or the formation of ice at the electrodes at low temperatures.

The cutoff criterion of the minimum terminal voltage $U_{Battmin}$ is fulfilled if the terminal voltage U_{Batt} falls below the specified minimum terminal voltage $U_{Battmin}$.

The criterion of the minimum capacity is met if a line voltage such as, for example, the voltage at a load powered by the energy store would sink below a specified threshold value if the energy store would have the load placed on it over a specified time period. To establish whether the load voltage in a specified load current characteristic would sink below a specified threshold value, a voltage predictor is provided, which ascertains the associated load voltage as a function of the load current characteristic. In a motor vehicle it is thus possible to ascertain how much charge is still able to be drawn from the motor vehicle battery given a specified

discharge current and battery temperature characteristic before there is only an amount of charge remaining that is sufficient for the line voltage at an electrical load to be connected at a specified load current characteristic not to fall below a specified threshold value. In the case of a motor vehicle electrical system, this is especially necessary so as to prevent more charge from being taken from the battery than is required, for example, for a new starting procedure.

Alternatively, other cutoff criteria may be defined as well.

At specified temporal intervals, the charge predictor repeats the ascertainment of the charge able to be drawn from the energy store, in each case taking current values for the discharge current $I_{Batt,entl}$ and the energy store temperature $T_{Batt,entl}$ into account. The charge predictor may also be capable of determining the time until the specified cutoff criterion is met.

The state and parameter estimator works on the basis of the same energy store model as the charge predictor.

Brief Description of the Drawings

Fig. 1 shows a schematic representation of a device according to the present invention for ascertaining the charge able to be drawn from a battery, the device having a charge predictor and a voltage predictor.

Fig. 2 is an equivalent circuit diagram for a lead accumulator.

Fig. 3a is a flow chart illustrating the method steps in calculating the charge able to be drawn using a charge predictor.

Figs. 3b and 3c show a flow chart illustrating the checking of different cutoff criteria.

Fig. 3d is a flow chart illustrating the method steps in calculating a minimum battery voltage using a charge predictor.

Fig. 4 is a graph illustrating the dependence of the electrolyte voltage on different physical effects.

Detailed Description

1. Device for ascertaining the charge able to be drawn

Figure 1 shows a block diagram of a device for calculating the charge able to be drawn from a battery, e.g., a vehicle battery. This includes a state variable and parameter estimator 1, a charge predictor 2 and a voltage predictor 3. The device is capable of calculating the charge able to be drawn from the battery (not shown) starting from a current battery state U_{Batt}, I_{Batt}, T_{Batt} and a specified discharge current characteristic $I_{Batt,entl}$ until a specified cutoff is reached. The discharge current characteristic $I_{Batt,entl}$ in this case may be an arbitrarily specified current characteristic or a constant current (I_{Batt}).

Charge predictor 2 and voltage predictor 3 include a mathematical battery model, which describes the electrical properties of the vehicle battery. Knowing the current performance quantities of the battery, that is, current battery voltage U_{Batt}, current battery current I_{Batt} and current battery temperature T_{Batt}, as well as taking into account a specified discharge current characteristic $I_{Batt,entl}$ and a specified temperature characteristic $T_{Batt,entl}$, it is thus possible to calculate the charge able to be drawn from the battery $Q_{e,Ukrit}$, $Q_{e,UBattmin}$, $Q_{e,ULastmin}$ until three different cutoff criteria (which are conjunctively combined in the

present example) are met. Discharge current characteristic $I_{Batt,entl}$ and temperature characteristic $T_{Batt,entl}$ during discharge may either be specified by a control unit (not shown) or may be ascertained from the current performance quantities of the battery U_{Batt}, I_{Batt}, T_{Batt}.

Charge predictor 2 and voltage predictor 3 include a mathematical battery model, which mathematically describes the electrical properties of the vehicle battery and is based on the equivalent circuit diagram for a lead accumulator shown in Figure 2.

2. Equivalent circuit diagram of a lead accumulator

Figure 2 shows the equivalent circuit diagram of a lead accumulator. As is customary, the counting direction of battery current I_{Batt} was chosen to be positive for charging and negative for discharging. The individual state variables and components are as follows, from left to right:

$R_i(U_{C0}, U_e, T_{Batt})$	Ohmic internal resistance, dependent on open-circuit voltage U_{C0}, electrolyte voltage U_e and acid temperature T_{Batt}
U_{Ri}	Ohmic voltage drop
C_0	Acid capacity
U_{C0}	Open-circuit voltage
R_{F} (U_{C0}, T_{Batt})	Acid diffusion resistance, dependent on open-circuit voltage U_{C0} (degree of discharge) and acid temperature T_{Batt}
$\tau_k = R_k * C_k$	Time constant of acid diffusion (is assumed to be constant in the order of magnitude of 10 min)

U_k	Concentration polarization
$U_e=U_{C0}+U_k$	Electrolyte voltage
$\Delta U_{Nernst}(U_e, T_{Batt})$	Voltage difference between the terminal voltage and electrolyte voltage U_e, dependent on electrolyte voltage U_e and acid temperature T_{Batt}
U_D (I_{Batt}, T_{Batt})	Stationary charge transfer polarization, dependent on battery current I_{Batt} and acid temperature T_{Batt}
U_{Batt}	Terminal voltage of the battery

The individual variables are attributable to different physical effects of the battery, which are briefly explained in the following:

Voltage U_{Ri} is the ohmic voltage drop at internal resistance R_i of the battery, which in turn depends on open-circuit voltage U_{C0}, electrolyte voltage U_e and acid temperature T_{Batt}.

Open-circuit voltage U_{C0} is proportional to the average acid concentration in the battery and is equal to the terminal voltage of the battery if the acid concentration following a rest phase of the battery is of the same magnitude everywhere.

Concentration polarization U_k takes into account the deviation of the acid concentration at the location of the reaction, i.e. at the electrodes, from the average value in the battery. As the battery discharges, the lowest acid concentration exist in the pores of the electrodes, since the acid is consumed there and new acid must first continue to flow in from the electrolyte.

Electrolyte voltage U_e takes into account the deviation of open-circuit voltage U_{C0} by the concentration polarization as a

function of the acid concentration at the location of the reaction. The equation $U_e = U_{C0} + U_k$ applies in this connection.

The term $\Delta U_{Nernst}(U_e, T_{Batt})$ describes the voltage difference between the electrode potential and the electrolyte voltage, which in turn depends on the local acid concentration at the location of the reaction and on acid temperature T_{Batt}.

Stationary charge transfer polarization $U_D(I_{Batt}, T_{Batt})$ takes into account an electrical transfer resistance between a first electrode of the battery and the electrolyte and between the electrolyte and the second electrode of the battery, and is in turn dependent on battery current I_{Batt} and acid temperature T_{Batt}.

The diffusion of the acid from the electrolyte to the location of the reaction, i.e. to the electrodes, during discharge is described by acid diffusion resistance $R_k(U_{C0}, T_{Batt})$, which in turn is dependent on open-circuit voltage U_{C0} and acid temperature T_{Batt}.

3. The mathematical energy store model

The mathematical energy store model includes several models, which describe the ohmic internal resistance of the battery $R_i(U_{C0}, U_e, T_{Batt})$, acid diffusion resistance $R_k(U_{C0}, T_{Batt})$, voltage difference $\Delta U_{Nernst}(U_e, T_{Batt})$ between the electrode potential and the electrolyte voltage, and stationary charge transfer polarization $U_D(I_{Batt}, T_{Batt})$. Alternatively, more or fewer mathematical models may be taken into account as well. For the individual variables listed below, other mathematical models may be applied as well.

3.1. Ohmic internal resistance:

$$R_i(U_{C0}, U_e, T_{Batt}) = R_{i0}(T_{Batt}) * (1 + R_{i,fakt} * (U_{C0max} - U_{C0}) / (U_e - U_{e,grenz}))$$

where

$$R_{i0}(T_{Batt}) = R_{i025}/(1+TK_{Lfakt}{}^{*}(T_{Batt}-25°C))$$

Where

R_{i025}	Ohmic internal resistance at full charge and $T_{Batt}=25°C$
TK_{Lfakt}	Temperature coefficient of the battery conductivity
$R_{i,fakt}$	Characteristics map parameter
U_{C0max}	Maximum open-circuit voltage of the completely charged battery
$U_{e,grenz}$	Electrolyte voltage at cutoff (dependent on ageing)

3.2. Acid diffusion resistance

To approximate acid diffusion resistance R_k, for example, the following model may be used:

$$R_k(U_{C0}, T_{Batt}) = R_{k0}(T_{Batt}) * (1+R_{k,fakt1}{}^{*}(U_{C0max}-U_{C0})+R_{k,fakt2}{}^{*}(U_{C0max}-U_{C0})^2+ R_{k,fakt3}{}^{*}(U_{C0max}-U_{C0})^3)$$

where

$$R_{k0}(T_{Batt})=R_{k025}*\exp(-(E_{Rk0}/J)/8.314*(1/(273.15+T_{Batt}/^{0}C)-1/298.15))$$ (Arrhenius approach)

and

R_{k025}	Acid diffusion resistance at full charge and $T_{Batt}=25°C$
E_{rk0}	Activation energy

$R_{k,fakt1}$, $R_{k,fakt2}$,
$R_{k,fakt3}$ Polynomial coefficients

3.3 Voltage difference ΔU_{Nernst} between the electrode potential and electrolyte voltage U_e

For the voltage difference between the electrode potential and the electrolyte voltage, the following model may be used, for example:

$$\Delta U_{Nernst}(U_e, T_{Batt}) = alpha*\exp(-(U_e-U_{ekn})/beta)+TK_{U00}*(T_{Batt}-25^{\circ}C);$$

where

alpha, beta,
U_{ekn} Characteristics parameter

TK_{U00} Temperature coefficient of the electrode potential

3.4. Stationary charge transfer polarization

For stationary charge transfer polarization U_D, the following model may be used:

$$U_D(I_{Batt}, T_{Batt}) = U_{DO}(T_{Batt})*\ln(I_{Batt}/I_{DO})$$

where

$$U_{DO}(T_{Batt})=U_{D025}*(1+TK_{UD01}*(T_{Batt}-25^{\circ}C)+TK_{UD02}*(T_{Batt}-25^{\circ}C)^2+TK_{UD03}*(T_{Batt}-25^{\circ}C)^3)$$

U_{D025} Stationary charge transfer voltage at $I_{Batt}=e*I_{DO}$ and $T_{Batt}=25^{\circ}C$

I_{DO} Charge transfer current for $U_D=0V$

TK_{UD01}, TK_{UD02},

TK_{UDO2} Temperature coefficients of the first, second and third order of the charge transfer polarization

3.5. Influence of the acid stratification in the battery

An acid stratification is built up in the case of lead batteries having a liquid electrolyte if the battery, starting from a low charge state, i.e., a low average acid concentration, is charged using high current. Due to the high charging current, acid of high concentration forms in the region of the electrodes (location of reaction), which due to its higher specific gravity sinks downward such that the acid of low concentration remains in the upper region. Because of this, in the event of acid stratification, the battery behaves like a battery of reduced capacity (and thus resulting in reduced charge able to be drawn), since only the lower battery region having the high acid concentration still participates in the reaction. In addition, due to the increased acid concentration in the lower region, the electrode potential is raised above the value of an unstratified battery. Since open-circuit voltage U_{C0} and acid capacity C_0 are ascertained and adapted by state variable and parameter estimator 1, the effect of the acid stratification on the charge able to be drawn is already implicitly taken into account in the charge prediction by charge predictor 2. The method thus also takes into account the reduction of the charge able to be drawn in the case of batteries having acid stratification.

4. Calculation of the charge able to be drawn from the energy store

Figure 3a shows the calculation of charge Q_e able to be drawn from a vehicle battery. To this end, charge predictor 2 performs a numeric calculation and ascertains state variables U_{C0}, U_k, U_e, ΔU_{Nernst}, U_{Ri} and U_{Batt} of the battery model from

Figure 2. In detail, the calculation is performed as follows:

In block 10, charge q_k drawn from the battery in a time step t_{sample} is calculated for an assumed discharge current characteristic $I_{Batt,entl}$ and iteratively added. Discharge current characteristic $I_{Batt,entl}$, for example, may be constant and correspond to battery current I_{Batt} or may be an arbitrarily specified current characteristic. The following equations apply:

$$q_{k+1}' = q_k' + I_{Batt,entl} * t_{sample}$$

$$t_{k+1}' = t_k' + t_{sample}$$

The starting values q_0' and t_0' for this calculation are:

$$q_0' = 0, \ t_0' = 0$$

This iterative calculation is continued until a specified cutoff criterion is fulfilled. The charge able to be drawn from the battery is then $Q_e = q_{k+1}'$, and the time still remaining before meeting the cutoff criterion at the specified discharge current $I_{Batt,entl}$ is $t_e = t_{k+1}'$.

In blocks 11 through 15, stationary charge transfer polarization $U_D(I_{Batt,entl}, T_{Batt,entl})$, open-circuit voltage $U_{C0,k+1}'$, concentration polarization $U_{k,k+1}'$, electrolyte voltage $U_{e,k+1}'$, the value $\Delta U_{Nernst,k+1}'$, ohmic voltage drop $U_{Ri,k+1}'$ and battery voltage $U_{Batt,k+1}'$ are calculated. The equations in detail are:

$$U_{C0,k+1}' = U_{C0,0}' + q_{k+1}'/C_0'$$

Starting values: $U_{C0,0}' = U_{C0}$, $C_0' = C_0$

$$U_{k,k+1}' = U_{k,k}' + (I_{Batt,\ entl} * R_k(U_{C0,k+1}', T_{Batt,entl}) - U_{k,k}') * t_{sample}/tau_k$$

$$U_{e,k+1}' = U_{C0,k+1}' + U_{k,k+1}'$$

$\Delta U_{Nernst,k+1}'=alpha*exp(-(U_{e,k+1}'U_{ekn})/epsilon)\ +TK_{U00}*(T_{Batt,entl}-25°C)$

Starting values: $U_{k0}' = U_k$, $R_{k025}' = R_{k025}$

$U_{Ri,k+1}' = R_i(U_{C0,k+1}', U_{C0,k+1}', T_{Batt,\ entl})*I_{Batt,entl}$

Starting values: $R_{i025}' = R_{i025}, U_{e,grenz}' = U_{e,grenz}$

$U_{Batt,k+1}' = U_{Ri,k+1}' + U_{e,k+1}' + {}^{o}U_{Nernst,k+1}' + U_D'$

Here, $U_{Batt,k+1}'$ having index k+1 is a new value following an iteration. The iteration is performed until a specified cutoff criterion, in the present example simultaneously three different cutoff criteria, is fulfilled.

The comparison of the state variables with the different cutoff criteria is represented in Figures 3b and 3c. The first cutoff criterion is the reaching of a critical electrolyte voltage $U_{e,krit}$, which is determined by the acid concentration in the electrolyte, the battery temperature $T_{Batt,entl}$ and a voltage limitation by active mass loss of the battery electrodes $\Delta U_{e,grenz}$. In step 21 of Figure 3b, a check is performed for each iteration step k as to whether the electrolyte voltage $U_{e,k+1}'$ is smaller than or equal to the critical electrolyte voltage. If this is the case, then in step 22 a corresponding flag $flag_{Ue,krit}$ is set to logical "1" (TRUE). The charge able to be drawn Q_e in the case of this cutoff criterion is therefore $Q_{e,Uekrit} = q_{k+1}'$, and the period of time before the cutoff criterion is met is $t_{e,Uekrit} - t_{k+1}'$.

In parallel to step 21, a check is performed in step 24 as to whether a second cutoff criterion has been met. To this end, a check is performed to determine whether battery voltage $U_{Batt,k+1}'$ is smaller than or equal to a specified minimum battery voltage $U_{Batt,min}$. If this is the case, then again a specific flag identified as $flag_{UBattmin}$ is set to TRUE. The

charge able to be drawn $Q_{e,Ubattmin} = q_{k+1}'$ and the time $t_{e,UBattmin}$ required to reach this cutoff criterion is $t_{e,Ubattmin} = t_{k+1}$.

Finally, in step 26 (see Figure 3c), a check is performed as to whether the third cutoff criterion, that is, a required minimum capacity of the battery, has been reached. To this end, a check is performed to determine whether a load voltage U_{Last} dropping at a specifiable load would during a specified load current characteristic I_{Last} become smaller than or equal to a minimum load voltage $U_{Last,min}$ if the load were switched on at a specifiable time. Load voltage U_{Last} is thus the voltage that ensues at the load or e.g. at the battery if the load having a specified load current characteristic I_{Last} were switched on for a specified period of time t_{Last}. The background for this calculation is that for the time period t_{Last} it is to be ensured that the line voltage (or load voltage) does not fall below a specified minimum value and that the load during its operating time t_{Last} is sufficiently supplied. For calculating load voltage U_{Last}, which sets in after a specified on-time t_{Last}, voltage predictor 3 is provided. Using the known models for state variables U_{C0}, U_k, U_e, ΔU_{Nernst}, U_{Ri} and U_D, the latter calculates battery voltage U_{Batt} (step 36) at a specified load current characteristic I_{Last} and via a specified load on-time t_{Last}. The minimum value of battery voltage U_{Batt} from all iteration steps (step 37) following the expiration of load on-time t_{Last} (step 38) is equal to the load voltage U_{Last} (step 39).

In blocks 30 through 36 (see Figure 3d), voltage predictor 3 uses the same calculation models as the charge predictor for calculating the battery state variables with the difference that the calculation is based on a load current characteristic I_{Last}. Load current characteristic I_{Last} for example is the current which a load such as for example the starter motor in a motor vehicle requires for operation. Load current

characteristic I_{Last} and on-time t_{Last} may, for example, be specified by a control unit. The following equation applies:

$$q_{k+1}''=q_k''+I_{Last}*t_{sample}$$

$$t_{k+1}''=t_k''+t_{sample}$$

In block 26, minimum battery voltage U_{Last} occurring in the load simulation is compared to a threshold value $U_{Last,min}$ and it is established whether minimum load voltage U_{Last} is smaller than or equal to voltage $U_{Last,min}$.

Voltage predictor 3 calculates minimum voltage U_{min} at a specified load current I_{Last} in every iteration step of charge predictor 2. If the simulation yields the result that the minimum capacity has been reached ($U_{Last} <= U_{Last,min}$), then a specific flag identified as $flag_{ULastmin}$ is set to TRUE. The charge Q_e able to be drawn up to this third cutoff criterion is:

$$Q_{e,ULastmin} = q_{k+1}'.$$

In the case of specified discharge current $I_{Batt,entl}$, the minimum capacity of the battery is reached within a time

$t_{e,ULastmin} = t_{k+1}'$ (block 27).

If the cutoff criteria have not been met in steps 21, 24 and 26, then, just as after blocks 22, 25 and 27, a check is performed in step 28 as to whether all three cutoff criteria are fulfilled simultaneously. If this is the case, then the minimum value of the charges able to be drawn $Q_{e,Uekrit}$, $Q_{e,UBattmin}$, $Q_{e,ULastmin}$ are output as the maximum charge able to be drawn. At the same time, the associated duration t_e may also be output. If it is not the case, the calculation is continued.

In the case of a constant discharge current $I_{Batt,entl}$ = constant and a constant temperature $T_{Batt,entl}$ = constant, state variables

U_{C0}' and U_k' as well as battery voltage U_{Batt}' may also be calculated analytically such that the computing-time-intensive iterative calculation according to Figure 3a on the part of charge predictor 2 may be eliminated.

5. Definition of the first cutoff criterion

The charge able to be drawn from a battery depends essentially on the acid contained in the electrolyte. In addition, the discharge termination secondly also depends on the active mass (Pb, PbO_2 in the case of lead accumulators) in the electrodes of the battery accessible during the discharge process and thirdly on the electrolyte icing at low temperatures. The precision of the charge able to be drawn may be substantially improved by taking into account at least one of the above-mentioned effects.

5.1. Acid limitation

In the case of new batteries and batteries having a low active mass loss, the discharge of the battery is essentially limited by the acid contained in the electrolyte (acid limitation). For the acid concentration at the location of the reaction (electrodes), the electrolyte voltage U_e proportional to this acid concentration is used in the charge predictor's calculation of the charge able to be drawn. Typical boundary values for new batteries are e.g. $U_{e,krit}$, acid = 11.5 V at discharge termination (see branch b in Figure 4).

5.2. Active mass limitation

In the case of batteries having a higher active mass loss, the discharge termination (the battery no longer provides any charge) sets in already at higher voltages due to the depletion of the active mass (Pb, PbO_2) available for the discharge reaction. Figure 4 shows this shift of the critical

electrolyte voltage $U_{e,krit}$ by a value $\Delta U_{e,grenz}$ in the direction of higher voltages (from 11.5 to 12V; from branch b to branch c). Hence, taking into account the active mass limitation, the following relationship can be applied:

$$U_{e,krit,Masse} = 11.5\ V + \Delta U_{e,grenz}$$

5.3. Electrolyte icing

At temperatures below -10°C, electrolyte icing may occur particularly in the case of a low acid concentration. In this case, the supply of acid to the location of the reaction at the electrodes is inhibited such that a low acid concentration exists at the electrodes (see branch a in Figure 4). For the critical electrolyte voltage, the following temperature-dependent relationship may be assumed:

$$U_{e,krit,Eis}(T_{Batt}) = 11.423V - 0.0558V*(T_{Batt}/°C) - 0.0011V*(T_{Batt}/°C)^2 - 1.0*e\text{-}5V*(T_{Batt}/°C)^3$$

Taking all three effects into account, the following relationship can be used for the first cutoff criterion (reaching a minimum electrolyte voltage U_e):

$$U_e = U_{e,krit} = \max(U_{e,krit,Säure}, U_{e,krit,Masse}, U_{e,krit,Eis})$$

Figure 4 again shows the resulting characteristic of critical electrolyte voltage $U_{e,krit}$ as a function of battery temperature T_{Batt} and $\Delta U_{e,grenz}$.